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1.06 and 1.3 μm resonant cavity-enhanced photodetectors based on InGaAs quantum dots

I. L. Krestnikov, N. A. Maleev, M. V. Maximov, A. F. Tsatsul'nikov,
A. E. Zhukov, A. R. Kovsh, I. V. Kochnev, N. M. Shmidt, N. N. Ledentsov,
V. M. Ustinov, P. S. Kop'ev, Zh. I. Alferov and D. Bimberg†

Ioffe Physico-Technical Institute, St Petersburg, Russia
† Institute für Festkörperphysik, Technische Universität Berlin,
Hardenbergstr. 36, D-10623 Berlin, Germany

Photodetectors operating at the optimum wavelength for high-bit-rate, long-haul optical transmission systems (1.06, 1.3 and 1.55 μm) are of great practical importance and a subject of significant interest in research. To date, most of this work has utilized the InP/InGaAsP materials system, as the bandgap of the InGaAsP alloy can be adjusted to produce light emitters and detectors in the required wavelength range while keeping lattice matching with the InP substrate. On the other hand, using the strained InGaAs quantum dots (QDs) on GaAs substrates also allows to achieve the required wavelength range [1, 2]. The next step to improve photodetectors is to use a three-dimensional (3D) optical confinement for photons. It has been shown that the use of a Fabry–Perot resonant microcavity leads to an enhancement of the quantum efficiency, improved bandwidth, and better wavelength selectivity [3]. Distributed Bragg reflectors (DBRs) which are necessary for efficient microcavity resonators can be hardly obtained in the InGaAsP system due to low difference of refractive indices. While the GaAs/AlAs DBRs of good quality can be easily prepared. Taken together these facts: appropriate wavelength of the QD transitions and high performance GaAs/AlAs DBRs, one can conclude that the InGaAs/GaAs/AlAs system on a GaAs substrate is very beneficial for designing and fabricating the resonant cavity-enhanced (RCE) photodetectors [4, 5]. In this work we discuss optical properties of the structures with GaAs/AlAs DBRs and InGaAs QDs used as an active medium of the device.

The schematic view of the studied structures is shown in Fig. 1. First, bottom GaAs/AlAs DBR was grown on the GaAs (100) substrate by metal-organic chemical vapor deposition (MOCVD) (structure A) or molecular beam epitaxy (MBE) (structures B and C). Structure A consisted of 25 AlAs/GaAs periods, structure B—12 periods and structure C—22 periods. Then, a GaAs $2\lambda/n$ (n—refractive index, $\lambda = 1.3\,\mu$m for structures A and B and $\lambda = 1.06\,\mu$m for structure C) cavity region was grown by MBE for all structures. The special growth technique was used for structure A [6]. InGaAs QDs were introduced in the center of the cavity. Details of QDs growth are described elsewhere [1, 2]. The bottom part of the cavity was n-doped by Si and the top part was p-doped by Be. QDs were placed in an undoped layer having a 0.1 μm thickness. Together with the structure A a satellite structure without bottom DBR was grown during the same epitaxial run. For photocurrent measurements intracavity ohmic contacts were fabricated. Top SiO$_2$/ZnS DBRs (4 pairs) were deposited on structures B and C by thermal evaporation. Photoluminescene (PL) was excited by an Ar$^+$ laser (100 W/cm^2). A double-pass monochromator and a Ge-photodetector were used as detecting system. Light of a tungsten lamp was used for reflectivity measurements. For photocurrent investigations a light of the tungsten lamp passed through the monochromator and was focused on the RCE photodetector (1 mW/cm^2) by a microscope.
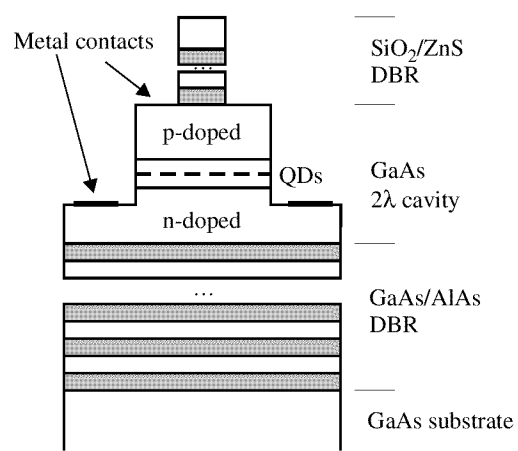
Fig. 1. Schematic view of the resonant cavity-enhanced photodetector structure.

In Fig. 2 PL spectra of structure A and its satellite (*a*) and an optical reflectance (OR) spectrum of structure A (*b*) are shown. The shape of the OR spectrum is defined by the GaAs/AlAs DBR which provides a very high reflectivity (better than 99.5%) as the sufficient number of periods in the DBR (25 GaAs/AlAs pairs) was grown. A cavity dip is not seen in the OR spectrum due to the low reflectivity of the air/GaAs interface. According to our computer simulations, the value of the dip is about 0.5% and cannot be well-resolved with our set-up.

PL spectrum of the satellite structure is typical for InGaAs QDs having optical transitions in the 1.3 μm-range [1], while the PL spectrum of structure A is dramatically changed by the DBR. The main peak is narrowed and its intensity is an order of magnitude higher than
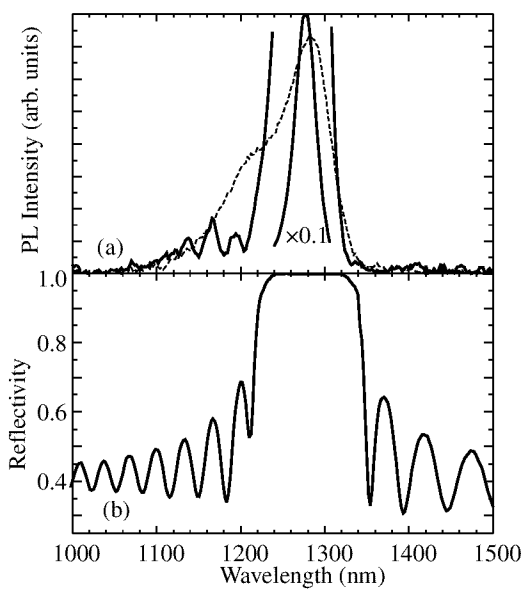

Fig. 2. Photoluminescence spectra of structure A and its satellite at 300 K (*a*) and optical reflection spectrum of structure A (*b*).
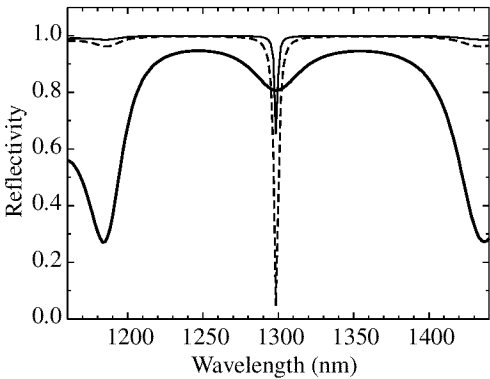
Fig. 3. Calculated optical reflectance (OR) spectra for structure B without (thick line) and with (thin line) top dielectric distributed Bragg reflector (DBR). Dashed line presents a calculated OR spectrum with top dielectric DBR having an antireflection coating.

that in the satellite structure. It can be explained by the formation of a standing wave in the microcavity at the resonant wavelength. In this case the line broading is caused only by finesse of the cavity. The second manifestation of the influence of DBR on the PL spectrum is the intensity oscillations on the short wavelength side of the peak. These oscillations are in an agreement with those in the OR spectrum. Thus, the effects of the resonant cavity-enhancements are evident even without the highly-reflecting top DBR. However, in this case the bandwidth is not narrow enough. To define proper parameters of the top dielectric (SiO_2/ZnS) DBR we performed a computer simulation of the OR spectra and the distribution of the electromagnetic field in the structure B.
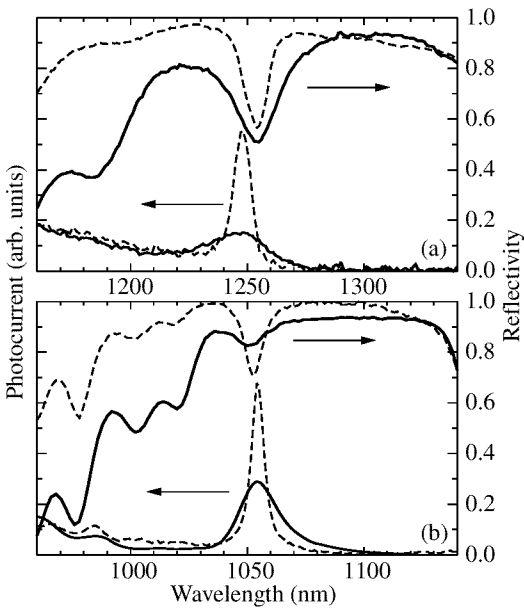

Fig. 4. Dependence of photocurrent *versus* wavelength and OR spectra for structures B (*a*) and C (*b*) without (solid line) and with (dotted line) top dielectric DBR.

The calculated OR spectra are shown in Fig. 3. As opposite to the case of the 25 pair AlAs/GaAs DBRs, in the case of only 12 pairs DBRs, the cavity dip is clearly seen in the calculated spectrum even without the top dielectric DBR (thick line). Using the top dielectric DBR dramatically improves the finesses of the cavity. It results in a narrowing of the cavity dip and in increase of its depth (thin line). However, due to the high reflectivity of the top DBR the most of the incident photons are reflected even at the resonant wavelength. To avoid the lose of the incident light it is possible to use an antireflection coating which is formed by increasing the thickness of the top ZnS layer up to the $\lambda/2n$ value. In the OR spectrum it results in a pronounced increase of the depth of the cavity dip (dashed line). In this case the most of the incident photons enters the structure and is adsorbed by QDs. This effect is also confirmed by the calculations of distribution of the intensity of the electromagnetic field in the structure. In the case of antireflection coating, the electromagnetic field intensity in the active region is much stronger than in the opposite case. Thus, for our devices we used dielectric DBR with top ZnS layer having a $\lambda/2n$ thickness.

Figure 4 shows dependence of photocurrent *versus* wavelength and OR spectra for structures B (*a*) and C (*b*) without (solid line) and with (dotted line) top dielectric DBR. One can see a resonant peak in photocurrent, which corresponds to the cavity dip in the OR spectra. Some detuning in wavelengths is caused by non-uniformity of the thicknessess of the epitaxial layers. As it follows from the calculations, the use of top dielectric DBR with antireflection coating results in an increase in depth and narrowing of the photocurrent peak. To improve these sensitivity of the device further, making it more attractive for device applications, it is necessary to use higher quality DBRs (similar to used in structure A). To overcome the problem of the slow growth rate in MBE, a set of structures with DBRs, having a large number of periods, were grown using MOCVD. The active region with QDs was grown by MBE on top of DBRs. Now these structures are under investigation.

In summary, we have fabricated RCE photodetectors with AlAs/GaAs DBRs and In-GaAs QDs used as an active medium operating at 1.06 and 1.3 μm wavelengths.

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